An Assessment of the United States Measurement System:

Addressing Measurement Barriers to Accelerate Innovation

Appendix G

Descriptions of Selected Broad Technologies

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Description of Selected Broad Technologies

This Appendix contains descriptions of the four broad technologies - nanotechnology, disaster first-responder technology, bio-medical imaging, and magnetic data storage - that were selected by the USMS Task Group to provide a snapshot of measurement barriers to technological innovation. These technologies are one of the four points of view discussed in Chapter 4 - Methodology of the Assessment.

Nanotechnology

Nanotechnology refers to materials, devices, and systems that have structures within the range of about 1 nm to 100 nm. At the nanoscale, the properties of matter change significantly from bulk properties because quantum effects and surface area effects may dominate.[1] Nanotechnology is selected in this Report as a national measurement issue because today, U.S. manufacturers are responsible for almost two-thirds of all private-sector R&D[2] and within the next 10 years, experts expect that at least half of the newly designed advanced materials and manufacturing processes will be at the nanoscale or incorporate nanoscale materials. U.S. industry faces many challenges in incorporating nanotechnology into these advanced products and processes.

The measurement of properties and dimensions, imaging of structures, and modeling of behavior are all difficult at the nano-scale and will require significant investment to avoid stifling the commercial development and manufacture of nano-structured products. Worldwide, nanoscale manufacturing is expected to be a dominant factor in the 21st century. The promise of the U.S. investment and innovation in nanoscience and nanotechnology will be realized only if our Nation can cost-effectively put basic scientific discoveries to work in the manufacturing of superior nanotechnology-related products. The global impact of nanotechnology-related products is predicted to exceed $1 trillion by 2015[3] (estimates include: Materials $340B; Electronics $300B; Pharmaceuticals $180B; Chemicals $100B; Aerospace $70B; Healthcare $30B; and Tools $20B). The opportunities associated with these challenges are far-reaching. In the U. S. economy, commercial incorporation of nanotechnology is projected to have dramatic effect on U. S. industry sectors, such as: microelectronics; magnetic storage; micro-electromechanical system; nanomaterials and nano-composites, instrumentation, pharmaceuticals and catalysts. Accurate and reliable measurement results are critical to industry's ability to make progress in the highly nanotechnology-dominated production environment of the future.

Recent national workshops support the conclusion of the National Nanotechnology Initiative's (NNI) that a strong measurements and standards infrastructure is essential for the large U.S. investment in nanotechnology to be scientifically, technologically, and economically successful.[4],[5] The NNI Strategic Plan[6]

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[1] O. Renn and M. C. Rocco, "Nanotechnology and the Need for Risk Governance," J. Nanoparticle Research, Vol. 8 (2), 2006.

[2] National Science Foundation, "Research and Development in Industry," 2000.

[3] M.C. Roco and W.S. Bainbridge, eds., 2001, "Societal Implications of Nanoscience and Nanotechnology", Springer, pp. 3-4.

[4] Chemical Industry Roadmap for Nanomaterials by Design, Sept 15, 2003. Available from the National Nanotechnology Coordination Office or downloaded from: www.nano.gov.

[5] NNI Grand Challenge Workshop on Instrumentation and Metrology. Available from the National Nanotechnology Coordination Office or downloaded from: www.nano.gov.

[6] NNI Strategic Plan, December 2004. Available from the National Nanotechnology Coordination Office or downloaded from: www.nano.gov.

outlines many measurement needs associated with nanotechnology. Additionally, some Industry Roadmaps, e.g., the 2005 International Technology Roadmap for Semiconductors[7] and the 2003 Chemical Industry Roadmap for Nanomaterials by Design[8] cite nanotechnology measurement needs.

Nanotechnology is a broad category covering all aspects of the use of nanoscience. Nanoscience is being applied to many fields and economic sectors, and there are consequently overlaps. Economic sectors addressed in this report that have measurement needs in nanotechnology include aerospace, agriculture and food processing, aluminum, chemicals, electronics (semiconductors and non-semiconductors), energy and power, environment, healthcare (diagnostics and bio-medical imaging), homeland security, and defense (equipment and medicine).

The lack of sufficient metrology to aid in the design process and to support design, development, and synthesis was cited as a key stumbling block to innovation in a number of case studies and technology roadmaps concerned with nanostructures and nanomaterials. Characterization, design and synthesis are closely linked to and directly support manufacturing of nano-devices. Resolving metrology issues in these applied research, pre-production development phases is often stated as being critical to moving forward to production of working devices.

Even though the preponderant majority of measurement need case studies (see Appendix B) for nanotechnology shows that regulation has little impact, others in the U.S. and elsewhere, particularly those in Europe, have published in both scientific journals and the popular press articles about the need for risk governance in nanotechnology[9]. Both international and national organizations, e.g., the International Risk Governance Council[10] and the European Nanotechnology Trade Alliance (ENTA), [11] have been established whose goals are to develop a balanced approach to regulating and governing risks associated with emerging technologies, especially, nanotechnology.

The role of regulation and risk management for all phases of nanotechnology from research to commercialization of selected research results will impact the acceptable solutions to measurement needs that pose barriers to technological innovation. Consider for example, the recent press release from ENTA[12] in which the United Kingdom's Department for Environment, Food and Rural Affairs (DEFRA) has proposed a voluntary reporting scheme for industry on engineered nanoscale materials. The scheme is designed to enable DEFRA to build an information base in a way that will allow an informed decision about the nature of appropriate controls.

Highlights from the USMS Technology Roadmap Review Summary Report prepared by Energetics, Inc. for the NIST USMS Project (Appendix C) are:

- Sensing and detection devices operating at the nanoscale for a myriad of applications, including:
  - detection and treatment of infection and nutrient deficiency
  - sensing of health problems
  - tracking of food pathogens and agricultural products

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[7] 2005 International Technology Roadmap for Semiconductors. http://public.itrs.net/

[8] 2003 Chemical Industry Roadmap for Nanomaterials by Design: From Fundamentals to Function, http://www.chemicalvision2020.org/nanomaterialsroadmap.html

[9] O. Renn and M. C. Rocco, "Nanotechnology and the Need for Risk Governance," J. Nanoparticle Research, VOl. 8 (2), 2006, see Section 3 therein.

[10] See http://www.irgc.org/irgc/

[11] See http://www.euronanotrade.com/

[12] See http://www.euronanotrade.com/index.php?option=content&task=view&id=449&Itemid=30

- nano-separation and nano-bioreactors
- ensuring food safety
- characterizing environmental impacts/soil degradation
- creating anti-fouling nano-surfaces (e.g., packaging).

- A broad range of metrology needs are associated with the understanding, characterization, synthesis, and manufacturing of new nanomaterials that include:
  - characterization tools, methods and instruments for properties measurement
  - tool development infrastructure
  - reference standards and protocols for synthesis and analysis protocols
  - robust manufacturing metrology
  - characterization, measurement and simulation probes for use during synthesis
  - measurements for environmental, health and safety impacts of nanomaterials.
- Metrology to support nanostructures as energy carriers (optimized energy transport)
- Metrology (characterization tools, theory, imaging, simulation) to link nanoscale structure and function for design of new nanomaterial architecture and assembly for energy applications (mass and energy transport, storage, conversion, production);
- Metrology and infrastructure to support scaleable synthesis of nanomaterials for unique energy applications; metrology to support use of carbon nanotubes for hydrogen storage.
- Characterize nanometer-sized zeolites and nanostructures for use as environmental catalysts;
- Metrology to support development of dispersed suspensions of nanoparticles without absorbed additives
- New nano-sensors and devices for detection of chemical, biological, radiological and explosive elements; nanomaterials for advanced protective clothing and filters and remediation of attacks.

Disaster First-Responder

A century ago, the tragic aftermath of the Great San Francisco Earthquake demonstrated to this country the need for measuring and understanding the threats that first responders face following a cataclysmic event. Since then, scientific measurements of public safety threats have helped emergency responders to develop more effective response procedures and enabled manufacturers to produce and laboratories to test equipment that allows public safety personnel to work safely in extremely hazardous conditions, both routine and extraordinary. As a result, tens of thousands of first responder and civilian lives have been saved.

Homeland Security poses fundamentally new challenges to both disaster first-response and to the science of measurement. On one hand are threats that were almost unimaginable on American soil a decade ago: chemical and biological agents, radiological materials, and military-grade explosives. Only recently have scientists and engineers begun to study these threats in detail and accumulate the knowledge needed to develop effective countermeasures, such as detection devices and protective equipment. On the other hand are the nature and scale of potential terrorist attacks. With major cities being likely targets, first responders must be prepared to conduct rescue and damage control operations in high-density urban environments. With the possibility that an attack could affect thousands of victims in an area measured in square miles, public safety and security agencies at all levels must be able to coordinate and effectively manage their operations across functional and jurisdictional boundaries. All of these require significant advances in technical disciplines ranging from imaging and robotics to personnel tracking and emergency communications.

Despite years of intense scientific effort in these and other areas, many technical questions remain unanswered, and thus the men and women of America's 54,000 law enforcement, public safety, and public security agencies -- and the civilians and property they protect -- remain in jeopardy. New types of measurements and refinements of existing types of measurements are the first step toward answering these questions.

This section of the report identifies fourteen critical case studies measurement needs related to disaster first-responders. Each case study briefly describes the technological innovations at stake, the technical challenges involved and approaches to solving them, and the potential impact on this country's economy and security. The following lists the case studies of measurement needs related to disaster first-responders.

- Performance Standards for Ultratrace Chemical Sensors
- Mass Spectrometric Sensors for Explosives Detection
- Firefighter Radio Communications
- Fire Fighter Locator
- Firefighter Respiratory Protection
- Millimeter-Wave/Terahertz Imaging
- Thermal Imagers for Firefighters
- Firefighter Protective Clothing
- Advanced User Interfaces for Urban Search and Rescue (USAR) Robotics
- Spectroscopic Detection of Explosives
- Advanced X-ray Diagnostics for Bomb Detection
- Improved Visible and Infrared Vision System for Law Enforcement
- Real-time Neutron Radiation Monitors
- Soft Body Armor

Highlights from the case studies and the Technology Roadmap Review Summary Report prepared by Energetics, Inc. for the NIST USMS Project are:

- Metrology for sensors and surveillance devices to improve homeland security alert capabilities – chemical, radiological, biological.
- Metrology to support links to telemedicine and telehealth systems that respond to attacks and natural disasters.
- Impact monitoring for the aftermath of biological, chemical, and nuclear attacks with more accurate and precise sensors, including personal fire sensors.
- Metrology tools, methods, and guidelines for measuring fire properties to enable better fire safety models; measurement and imaging techniques to understand wildfire behavior (fuel characterization, fire emissions, combustion chemistry, visual imagery of fire spread, remote sensing, generation of wildland fire fuel maps).

Bio-Medical Imaging

Imaging innovations are revolutionizing medicine.

> "The revolutionary capabilities of new 3D and 4D imaging modalities – CT, MRI, PET, Ultrasound, etc. – along with computer reconstruction and rendering of multidimensional medical and histologic volume image data … provide powerful new opportunities for medical diagnosis and treatment, as well as for biological investigations." *(Dr. Richard Robb, Mayo Clinic)*

Biomedical imaging is inherently interdisciplinary and requires the expertise of the physical, biological, and information technology sciences. As a result of much major advancement, biomedical imaging now has paramount status in life sciences and delivery of healthcare. Advances in biomedical imaging make it possible to non-invasively detect, diagnose, and guide therapies for a large variety of diseases and to increase the productivity of healthcare delivery. Biomedical imaging is a large part of the U.S. Government's efforts, especially, those at the National Institutes of Health (NIH) and the Veterans Administration. For example, the National Institutes of Health (NIH) established in 2000 the National Institute of Biomedical Imaging and Bioengineering (NIBIB).[13] The collective goals of these publicly funded efforts are to identify the most important challenges and opportunities in biomedical imaging science and to create strategies for integrating biomedical imaging with biological and medical research, development, and deployment of results.

Modalities

While tomographic and post-processing techniques become increasingly sophisticated in the use of both hardware and advanced computing, traditional and emerging modalities also have critical roles in anatomical, functional, cellular, molecular, and skeletal imaging. The scope of biomedical imaging involves:

- Data and image acquisition,
- Image reconstruction and processing, and
- Image analysis to extract useful information and to obtain quantitatively medical parameters.

It depends on theories, algorithms, and computing systems and applications.

Biomedical imaging is used at the cellular and molecular level, in the early detection of disease, in therapies, and for clinical trials and Informatics. Biomedical imaging equipment and procedures are tools for creating powerful images of the body and its diseases. Such images span broad applications that include viewing cells, complex tissues, bone fractures, herniated disks; detecting diseases such as osteoporosis and osteoarthritis; and locating and treating tumors in cancer patients. Innovative advances in imaging measurements will provide the breakthroughs needed to explore the human body in new and exciting ways and will provide the medical community with non-invasive tools for early detection of diseases, treatments of cancers and other diseases, targeted drug therapies, monitoring patients over time, and monitoring biomaterials used for joint, valve, and organ replacements.

Biomedical imaging includes the following modalities and techniques:[14]

- Digital radiography and tomosynthesis
- X-ray computed tomography (CT)
- Magnetic resonance imaging (MRI)
- Single photon emission computed tomography (SPECT)
- Positron emission tomography (PET)
- Dual X-ray Absorptiometry (DXA)
- Ultrasound imaging
- Diffuse optical tomography, coherence, fluorescence, bioluminescence tomography, impedance tomography
- Neutron imaging for biomedical applications
- Magnetic and optical spectroscopy, and optical biopsy
- Optical, electron, scanning tunneling/atomic force microscopy
- Small animal imaging

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[13] http://www.nibib.nih.gov/nibib/File/News%20and%20Events/report_19990625.pdf

[14] See http://www.hindawi.com/journals/ijbi/index.html

- Functional, cellular, and molecular imaging
- Imaging assays for screening and molecular analysis
- Microarray image analysis and bioinformatics
- Emerging biomedical imaging techniques
- Imaging modality fusion
- Biomedical imaging instrumentation
- Biomedical image processing, pattern recognition, and analysis
- Biomedical image visualization, compression, transmission, and storage
- Imaging and modeling related to systems biology and systems biomedicine
- Applied mathematics, applied physics, and chemistry related to biomedical imaging
- Grid-enabling technology for biomedical imaging and informatics

Measurements and Standards - Case Studies

Advances in measurement science and standards are needed to drive innovation in biomedical imaging systems and to enable the technologies to move from simple imaging to more clear-cut and quantitative identification of targeted areas and applications of treatments. This requires interdisciplinary approaches that include the physical, biological, and information sciences and technologies. Medical researchers and equipment developers now face barriers to technological innovation caused by the absence of critical measurement-related information and standards. Until these barriers can be overcome, biomedical imaging will move more slowly and timely improvements in medical treatments will be delayed or missed.

Among the 76 case studies, which are given in Appendix B of this Report, on measurement needs in the healthcare areas of bioimaging, informatics, and clinical diagnostics, about 33% or 26 case studies concerned one or more of the above modalities and techniques of biomedical imaging. These biomedical imaging case studies were submitted to the USMS program by the organizers, leaders, and participants in the following:

- NIST Strategic Working Group (SWG) for Biosystems and Health that identifies areas of highest impact for biosystems technologies and related healthcare technologies; identifies the measurements, standards, and data requirements for these areas; and defines NIST's potential role and strategies.
- Bio-photonic Tools for Cell and Tissue Diagnostics - USMS Workshop that produced measurement need case studies in the area of medical biology diagnostic techniques. Bio-photonics is the intersection of photonics and biology in which light is used to image, detect, and manipulate biological materials.
- Standards and Measurements for Assessing Bone Health - USMS Workshop that produced measurement need case studies for DXA scans used to detect bone diseases such as osteoporosis and then to monitor patients' responses to therapies. This Workshop listed 10 measurement needs in priority order.
- Imaging Metrology in Telemedicine - two USMS Workshops that produced measurement need case studies on interoperability, image quality, and calibration of portable bioimaging devices. Metrology for assessing image quality is crucial not only for telemedicine but in all of the modalities listed above.
- Imaging as a Biomarker - Standards for Change Measurements in Therapy - USMS Workshop that will be held September 14 – 15, 2006. The scope of this workshop is focused on the need to standardize imaging methods for data collection and data analysis in the context of drug or radiation therapy trials.

Common Themes

Common themes among the above biomedical imaging case studies include:

- Biomedical imaging modalities often lack measurements and standards that are traceable to standards organization, such as calibration phantoms with reference data. Medical, manufacturers, and regulatory communities are concerned, but together they may lack an effective and functional infrastructure to develop such traceability for all biomedical-imaging modalities.
- Measurements to determine interoperability among components in imaging systems and networks and to determine compliance with standards and best practice operating procedures.
- Measurements and standards to assess image quality, manage color and gray scales across different image processing and display platforms, and to maintain integrity of image data over networks, especially, networks with high traffic.
- Performance metrics for both fixed and mobile devices - image acquisition, image processing, and display; examples include, 1) ranges over which pixel values are linear and 2) robustness of compression/decompression hardware and software.
- New measurement modalities and image analysis tools are needed to provide temporal, spatial, chemical, and mechanical data that are not accessible with current methods.
- Measurement science and standards are needed to drive innovation in imaging systems – enabling the technologies to move from simple imaging to more clear-cut and quantitative identification of targeted areas and applications of treatments.
- Edge detection techniques, algorithms for processing image data, and the characteristics of x-ray and optical sources are critical components in many biomedical imaging modalities. But, most companies that provide biomedical imaging equipment, software, and services treat edge detection methods and x-ray and optical sources as proprietary and do not make them publicly available to those promoting traceability and standards. Additional calibration artifacts and phantoms, substantial amounts of reference data, and extensive training for technologists must then be used to accommodate the proprietary aspects of edge detection and x-ray and optical sources. This is not a satisfactory solution from the perspective of the users because more costs are involved and the precision and accuracy of the measurements are compromised.
- Development of standards for image quality control, image data collection, and benchmarking of change analysis software tools, and image-specific statistical methods could significantly reduce the cost of healthcare research.

Examples of Recent Advances and Roadblocks to Deployment

Optical Imaging: Recent advances in optical (photonic) imaging promises to provide clinical information arising from changes in the characteristics of lights (ultraviolet, visible or infrared) when it interacts with tissue. The fundamental advantage of *in vivo* (within the body) optical imaging is that it can directly provide molecular information, which will be invaluable to understanding diseases and the effectiveness of their treatments. Additionally, advances in ultrasound imaging promises to provide insight into the interaction of advanced biomaterials used for joint, valve, and organ replacements and the effect that these materials may have on the human body. Finally, the integration of images from a variety of techniques will provide methods for visualizing a patient in three dimensions, combining anatomical, functional, and physiological information. Together, this information will provide medical professionals with a personalized view of the patient, providing vivid diagnostic images that pinpoint problematic areas and suggest tailored therapeutic treatments. Medical researchers and equipment developers now face roadblocks in reaching this goal due to the absence of critical measurement-related information and standards. Until these barriers can be overcome, the recent advances in biomedical imaging will move relatively slowly towards deployment and enormous improvements in medical treatments will be delayed or missed.

Cell and Tissue Measurements: Imaging is widely recognized as a powerful approach to gain insights into cell and tissue behavior. But, understanding and predicting the behavior of cells and tissues at the molecular level is hampered by a lack of established and accepted experimental and analytical protocols and standards, which limits comparative analysis and the combining of data from different sources. In addition, new measurement modalities and image analysis tools are needed to provide temporal, spatial, chemical, and mechanical data that are not accessible with current methods. A significant problem is the inability to compare imaging results obtained on between laboratories and instruments. The cells comprising biological tissues respond to a large number of physical and chemical parameters in their environment through complex networks of intersecting signal pathways. While imaging is the most promising approach to understanding these pathways, the metrology infrastructure for bioimaging does not currently exist. This impedes its use in improving development of drug and cell-based therapies and diagnostics.

Standards for Software Validation and Image Information Exchange: Over the next decade the preponderance of primary medical image reading for measurement of drug response and for diagnosis will be automated. The algorithms and software used in this analysis must be fully characterized and validated. Standardized reference databases containing uniform and accurate imaging data and information provide a means to evaluate analysis algorithm and software performance. In addition, the ability to integrate images from diverse imaging modalities as well as from different equipment manufacturers to facilitate the development of comprehensive databases of image information will improve quality and greater innovation in medical imaging. This ability will reduce the cost of healthcare. Stakeholders working together can develop the standard methods and technologies for capturing, exchanging, combining, interpreting, detecting and tracking changes, and visualizing data from various imaging techniques to increases diagnostic capabilities that will enable drug response measurement.

Magnetic Data Storage

The magnetic data storage industry is rapidly moving into metrology realms that exceed present measurement capabilities, driven by advances in areal density of magnetic recording media as it increases beyond 15 Gbit/cm^2. This advance translates to single bit dimensions that approach a few nanometers. Dimensional measurement at the nanoscale becomes a priority. New technologies being considered for commercial storage media include self-organized magnetic arrays, patterned films, heat assisted structures, perpendicular anisotropy media, and exchange-coupled layers. New device geometries and operation paradigms required for read heads and magnetic random access memory (MRAM) will also play a key role in future developments. Not only is scale important in these innovative devices, but also the recording industry must now deal with nanoscale effects at picosecond time scales and the impact of thermal changes of hundreds of degrees kelvin.

The case studies measurement needs for magnetic data storage show that the currently available metrology capabilities are challenged by both near and longer-term technical requirements. This state of affairs forces industry and academia to use either custom metrology or trial and error technology development. The following metrology innovations are needed to:

- fabricate magnetic structures with 1 nm to 10 nm dimensions
- measure their chemical properties and structure
- measure the magnetization vector at the atomic and few nanometer level nanoparticle in these structures to better understand their interactions
- image magnetic domain structures with 1 nm resolution
- probe magnetic interactions in buried layers
- develop modeling methods for handling multi-size scales ranging from 1 nanometer to 1 meter

In addition, the above measurements are needed in actual operating environments and must perform at picosecond time scales. Observation and measurement of magnetization reversal by domain processes or spin rotation methods are needed to enable engineering of devices for high speed switching and sensing. Targeted development of the underlying metrology and instrumentation is needed to make reliable reproducible measurements of device performance and materials' properties should enable the successful incorporation of next and future generation devices into commercial data storage products.

The 46 case studies produced by the Workshop on **Metrology for the Magnetic Data Storage Industry** identified the following measurement needs that may pose technological barriers to continued innovation:

- There is no single industry-standard method for the measurement of the frequency response of the hard disk drive (HDD) head gimbal assembly. There are substantial variations of results within and among the different measurement systems in use.
- Currently, there is no measurement method that correlates the abrasion property of tapes as measured with the observed wear of tape heads.
- There is no effective and standardized method for measuring the thickness of the protective coating, including the thickness of the lubrication film, on magnetic tape required to take into account that component of the overall tape-to-head spacing.
- There is no effective and standardized method for measuring the thickness of the magnetically inactive layer that takes into account the following effects:
    - a magnetically inactive layer can be induced on the tape head by machining processes in its fabrication,
    - tribo-chemical and electro-chemical processes with interaction of shields and poles and recording devices, and
    - mechanical contact with the tape in operation.
- There is no current measurement technique that can locate and measure the movement of magnetic domain walls within a tape read head, with the dimensions, geometry, and magnetic characteristics of next-generation tape systems.
- Instrumentation does not exist to measure the relative position of magnetic tape to tape head with the required resolution, accuracy, portability, and cost.
- The major challenge is to measure the extremely small magnetic moments of the nanometer-scale thin-films that are part of new-technology magnetic tape systems, such as giant magneto resistance (GMR) sensors.
- Measurements of the pole tip (or device) recession (PTR)**:** This is the static recession of the recording devices with respect to the arithmetic mean of the tape bearing surface. Attainable accuracies appear to be of the order of 3 nm at best. Accuracies of less than 1 nm are required right away and less than 0.4 nm will be required by 2015.
- The current method to measure the width of a read sensor is to estimate it by the output voltage of the sensor as it is scanned across a special micro-track written on a tape whose width is no more than one-quarter that of the sensor. Increased accuracy in the method is needed, as is improved control of the many variables associated with running tape over a head.
- There is no effective and standardized method for measuring the parameter called “mean compressed tape asperity height”, which is defined as the mean spacing between a contoured “smooth” glass head and a moving magnetic tape. Present methods lead to inaccuracies of greater than 5 nm. Accuracy less than 1.2 nm is required right now and < 0.4 nm will be required by 2015.
- Measuring the distribution of temperatures within the magnetic sensor of an operating magnetic tape head is needed.

- There are no off-the-shelf solutions to the problem of measuring head-disk friction of next-generation hard disk drives. Current friction-measurement methods lack the required precision, sensitivity, frequency response, and freedom from drift, to deal adequately with isolated individual and high-frequency intermittent head-disk contact events.
- Measurement of surface roughness of a lubricating film on a magnetic hard disk is needed.
- To characterize next-generation hard disk heads and disks enhanced measurement techniques are needed for hardness, yield strength, and other elastic and plastic properties of thin films. Stylus- or atomic force microscopies based approaches are inadequate to these needs.
- There is no method for direct measurement of Torque at the levels necessary and in the correct environment.
- There is no industry-standard and reliable method for the measurement of windage and there are substantial variations of results within and among the different measurement systems in use.